AIAA–2001–4927
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AIAA Conference & Exhibit on International Space Station Utilization
October 15–18, 2001 / Cape Canaveral, FL

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THE FCF COMBUSTION INTEGRATED RACK: MICROGRAVITY COMBUSTION SCIENCE ON BOARD THE INTERNATIONAL SPACE STATION

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ABSTRACT

The Combustion Integrated Rack (CIR) is one of three facility payload racks being developed for the International Space Station (ISS) Fluids and Combustion Facility (FCF). Most microgravity combustion experiments will be performed on board the Space Station in the Combustion Integrated Rack. Experiment-specific equipment will be installed on orbit in the CIR to customize it to perform many different scientific experiments during the ten or more years that it will operate on orbit. This paper provides an overview of the CIR, including a description of its preliminary design and planned accommodations for microgravity combustion science experiments, and descriptions of the combustion science experiments currently planned for the CIR.

INTRODUCTION

The ISS allows microgravity research to be conducted in space for periods of months or longer without needing to return the entire research laboratory to Earth each time an experiment is completed (Fig. 1). A primary facility for microgravity research on-board the ISS will be the Fluids and Combustion Facility (FCF). The FCF is being developed by the NASA Glenn Research Center in Cleveland, Ohio.[1,5] The FCF will support microgravity combustion and fluid physics research as outlined in the science requirements envelope document.[2]

The FCF consists of a Flight Segment and a Ground Segment. The FCF Ground Segment includes ground racks and equipment to be used for experiment development, astronaut training, telescience operations, and other essential Earth-based functions. The FCF Flight Segment comprises three on-orbit racks that will be located inside the U.S. Laboratory Module of the Space Station. These racks are the Fluids Integrated Rack (FIR), the Shared Accommodations Rack (SAR) and the Combustion Integrated Rack (CIR).

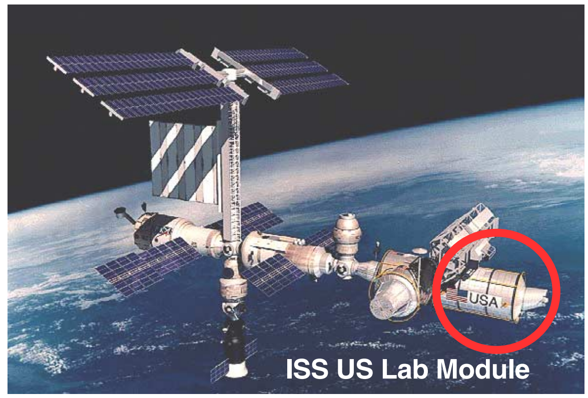

Figure 1. The International Space Station

The CIR will provide combustion research opportunities in extended microgravity conditions on board the ISS. It will be the first FCF rack deployed to the Space Station currently manifested on Utilization Flight #3 (UF-3). Initially, the CIR will operate independently from other FCF racks. Once the other FCF racks are deployed to ISS, the CIR will function together with those racks to provide a complete on-orbit research facility capable of meeting NASA Office of Biological and Physical Research Program objectives for sustained, systematic microgravity combustion research for the lifetime of the ISS (i.e., a minimum of ten years following ISS assembly complete).

CIR SYSTEM DESCRIPTION

The basic concept behind the CIR is that it provides up to 90% of the required hardware to perform a majority of future microgravity combustion experiments on board the ISS. The remaining 10+% of hardware will be provided by the PI hardware development teams. PI-specific hardware will be launched separately from the CIR and integrated with the CIR on orbit. A significant amount of PI hardware is expected to be reused for follow-on experiments. Since a majority of PI and CIR hardware is reused, this concept saves both development cost, total upmass (mass that is launched) and other ISS resources required to perform experiments on board the ISS.

The CIR consists of the following major subsystems and components (see Fig. 2)

- International Standard Payload Rack (-4 ISPR)

- Active Rack Isolation Subsystem (ARIS)
- Optics Bench on slides that tilts out of the ISPR
- Combustion Chamber with replaceable windows
- Fuel and Oxidizer Management Assembly (FOMA), including a gas supply package, exhaust vent system and gas chromatograph
- Modular, replaceable Science Diagnostics
- Environmental Control Subsystems, including water thermal control, air thermal control, fire detection/suppression, and gas interfaces
- Electrical Power Subsystem
- Avionics Subsystems, including the CIR main computer (Input/Output Package), image processing and storage units, FOMA control unit and Station Support Computer
- Flight and Ground Software
- Interfaces for replaceable, Experiment-Specific Equipment

The Subsystems common to all FCF Racks, and the experiment accommodations summary are described elsewhere[3,4,6] and the major sub-systems specific to the CIR are described below.

The CIR design allows different experiment packages within the combustion chamber to be removed, replaced or upgraded. Modular diagnostics are mounted on the optics bench and are easily repositioned.

The CIR and associated ground systems will offer the Principal Investigators the opportunity to participate in the conduct of their experiment on-board the ISS through remote operation and observation. Once a test point has been completed, the PI can assess the results and provide information for changes to the test matrix. Ground systems will also enable scientists to interact with researchers at other locations.

On-orbit capability for performing combustion experiments on board ISS will be enhanced when the SAR is installed. The SAR will provide a platform for pre- and post-experiment prcessing, and serve as a data handling rack for the FCF. Image processing computers supporting CIR diagnostics may be located in the SAR, allowing additional science diagnostics to be added to the CIR and enhancing the range of experiments which the CIR can accommodate. The SAR will also accommodate small, self-contained combustion experiments.

CIR SPECIFIC SUBSYSTEMS

Combustion Chamber

The CIR combustion chamber provides structural support and on orbit access for installation and removal of a combustion experiment insert with maximum dimensions of 60.0 cm long and 39.6 cm in diameter (Fig. 3). The Chamber Insert contains all of the experiment hardware such as fuel, igniters nozzles etc. The chamber is a cylindrical vessel with domed end caps that is centrally mounted to the optics bench. It has a one-hundred (100) liter free internal volume, an internal diameter of 40.0 cm and a length of 90.0 cm. A combustion experiment insert slides into the chamber from the front and is locked into position.

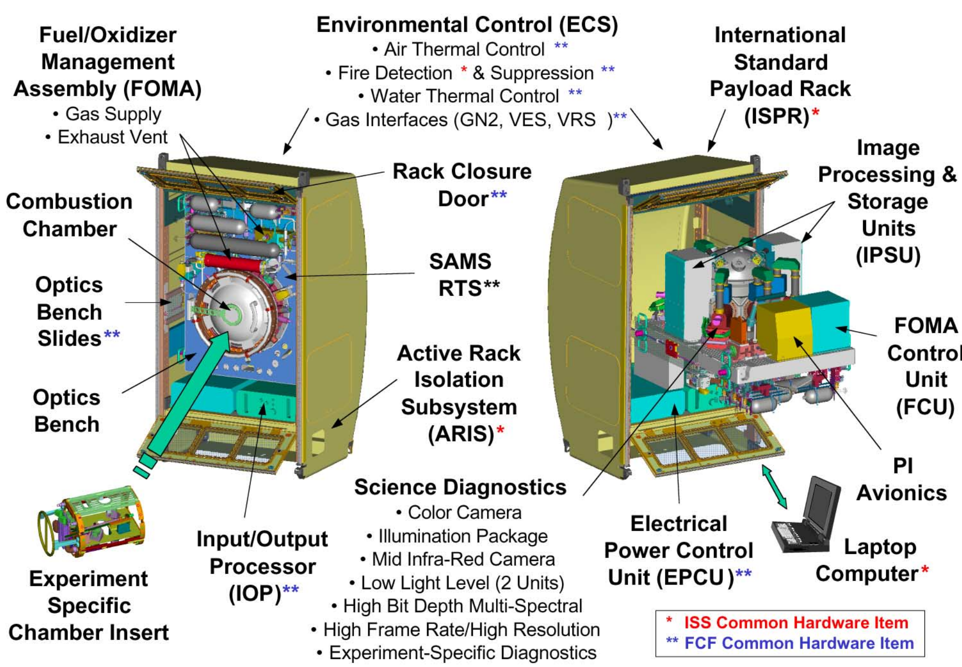

Figure 2. CIR components and subsystems

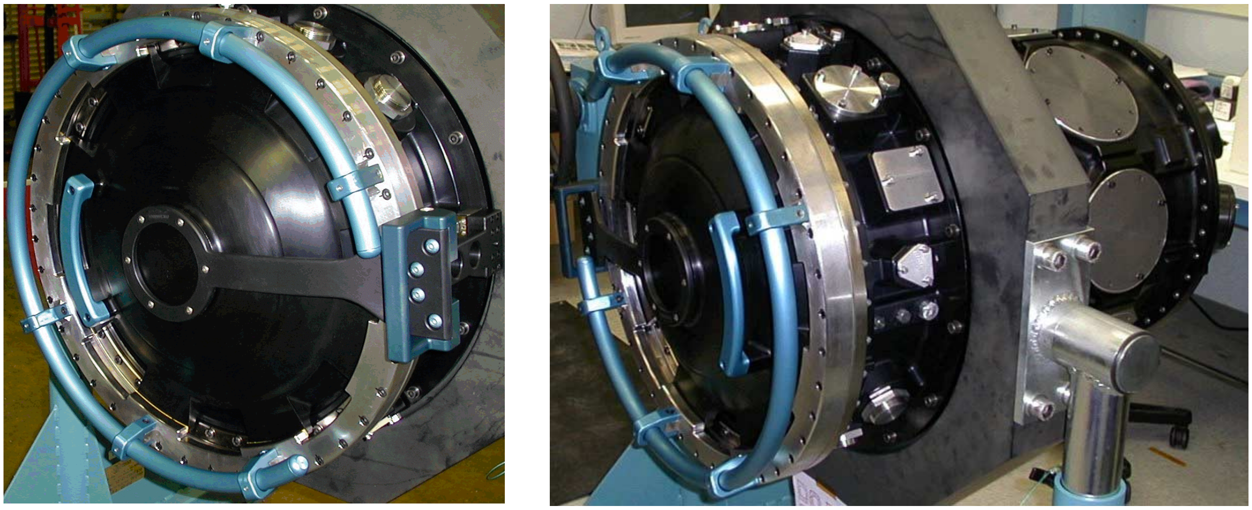

Figure 3. The CIR engineering model combustion chamber

Features:

- Provides structural support for the PI Hardware with on orbit access for installation and removal.
- Operates at pressures ranging from 0.02 to 3 atmospheres and has a maximum design pressure of 120 psig (approximately 8 atmospheres)
- The Chamber door is an 8-tab breech lock hinged front lid. No tools required to open
- The 8 windows are removable from inside the chamber for service and change-out. No tools required for replacement
- Baseline window material is sapphire
- Interface Resource Ring provides:
    - 4 electrical connectors
    - Inlet and outlet port for water cooling
    - 2 thermistors, 2 pressure transducers, 1 pressure switch
    - Nitrogen supply
    - Gaseous fuel/premixed
    - Partial pressure mixer
    - High pressure supply
    - GC Sampling
    - Exhaust Vent Port

Active Rack Isolation Subsystem

The CIR ISPR will be outfitted with an Active Rack Isolation System (ARIS) to isolate it from ISS vibrations. ARIS is designed to isolate an entire ISPR and its contents (Fig. 4). It attenuates on-orbit low frequency (<10 Hz), low amplitude mechanical vibrations that can be transmitted from the ISS US Lab Module to the CIR. The acceleration environment provided by ARIS is frequency dependent, but for frequencies between 0.01 and 10 Hz, ARIS is expect to limit accelerations in the CIR to micro-g levels.

Fuel and Oxidizer Management Assembly

A Fuel and Oxidizer Management Assembly (FOMA) provides the ability to safely deliver gaseous fuels, diluents and oxidizers to experiments in the CIR combustion chamber. The FOMA also samples the chamber environment using a gas chromatograph and controls the venting of chamber gases, at acceptable concentration levels, to the ISS Vacuum Exhaust System (VES). The FOMA consists a gas delivery package, an exhaust vent package and a gas chromatograph (GC). The Engineering Model FOMA is pictured on the front of the optics bench in Figure 5.

Gas Delivery Package—The Gas Delivery Package (GDP) consists of gas supply bottles and the necessary hardware and instrumentation to regulate and deliver up to three (3) gases to the combustion chamber. Gas bottles are located in the CIR on the front of the optics bench. Up to four gas bottles can be installed simultaneously in the CIR. The bottles are mounted using quick disconnects for rapid replacement by the

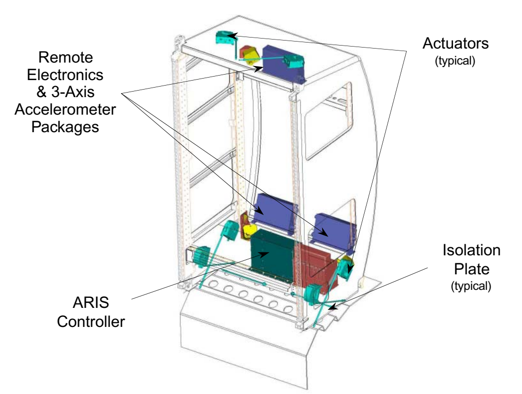

Figure 4. ARIS provides vibration isolation in CIR to meet science acceleration requirements

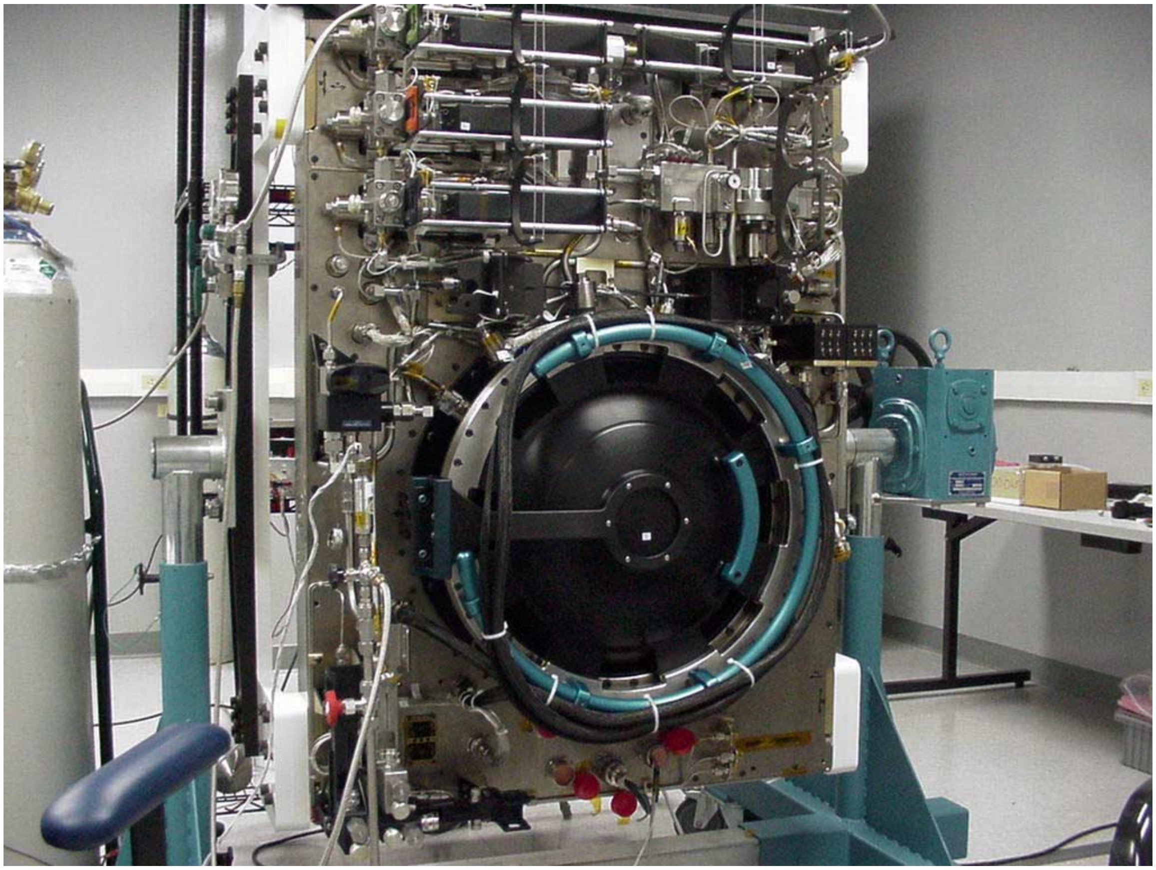

Figure 5. Engineering model FOMA on the optics bench

crew, as required for each experiment. Gas bottles installed in the CIR are for the active experiment only. Additional bottles required on-orbit are stowed.

Features:

- Gas is delivered through 1.0, 2.25, and 3.8 liter bottles
- Oxidizers bottles:
    - 1.0 liter up to 80% O_2
    - 2.25 liter up to 50 % O_2
    - 3.8 liter up to 30 % O_2
- Quick disconnects used for easy attachment to manifolds
- Provides chamber environment via partial pressure or dynamic gas blending
- Maximum oxidizer flow rates
    - 30 slm per manifold
    - 90 slm total
- Maximum fuel flow rate 2 slm

Exhaust Vent Package—The Exhaust Vent Package (EVP) connects the combustion chamber with the ISS vacuum exhaust. The EVP includes an adsorber cartridge and a recirculation loop to condition the chamber gas environment for the next test point or to convert post-combustion gases into species that are acceptable to vent. Chamber gases are pumped through the recirculation loop using two magnetically-coupled recirculation pumps mounted on the rear end cap of the combustion chamber at a maximum re-circulation flow rate is 20 SLM.

Features:

- Removes unacceptable species including water vapor, and particulates from the combustion event to allowable limits
- Manifolds located on front and back of bench
- Measures oxygen concentrations and dew point levels to assure ISS VES compliance
- Adsorber cartridges are customized to experiment requirements (e.g., Lithium Hydroxide, Activated Carbon, Silica Gel, and Molecular Sieve)
- Mass flow controller used to regulate vented gas

Gas Chromatograph—The combustion chamber environment can be sampled using a Gas Chromatograph (GC). The GC is a repackaged commercial unit with three (3) independent separation columns and sensors capable of utilizing different carrier gases, such as Helium, Hydrogen, Nitrogen, and

Argon. The 500 mL, 1,800 psia carrier gas bottles are sized to minimize bottle changeouts by the crew. The GC can accommodate up to four (4), 50 mL, 1,800 psia calibration gases. The GC lower detection limit is 100 ppm (depending on the compound) with an expected accuracy of $\pm$2%.

Science Diagnostics

Science diagnostics are used in the CIR to image combustion experiments. Diagnostics assemblies are mounted on the rear of the CIR optics bench at one of the eight universal mounting locations (UML) around the chamber and view the flame through optical windows in the chamber. A removeable latch mechanism, compatible with all science diagnostics packages, is used to attach and remove diagnostic assemblies from the optics bench.

Science diagnostic packages are constructed from modular optical components connected at standard interfaces to enable easy, on-orbit diagnostics package reconfiguration. Each package in the CIR consists of an Imaging Module, Optics Modules and a Diagnostics Control Module (DCM).

Seven standard diagnostic packages, constructed from these modular elements, are planned as initial diagnostic capabilities for the CIR (Fig. 6). These are a High Bit Depth/Multispectral Imaging Package (HiBM), a High Frame Rate/High Resolution (HFR/HR) Package, a Color Camera Package, two (2) Low Light Level Camera Packages, a Mid-IR Camera Package and an Illumination Package.

High Bit Depth/Multi-Spectral Imaging Package—The HiBMS package consists of a spectrally filtered, telecentric optical system and a high resolution, 12-bit output digital camera. The HiBM Package can be used to measure soot volume fraction and soot temperature of soot-producing flames. It can be used for shadowgraph measurements by adjusting the lens aperture and filter.

Features:

- Numerical Aperture: 0.005 to 0.02
  - Focus at chamber centerline
  - Field of View: 50 mm square or 80 mm diameter
  - Resolution: 10 lp/mm maximum (0.05 mm)
- Liquid Crystal Tunable Filter (LCTF)
  - 10 nm FWHM bandpass
  - 650 to 1050 nm spectral range
  - 1 nm spectral resolution
  - 100 ms switching time between states
- Programmable frame rate (7.5, 15 or 30 fps) and exposure time

High Frame Rate/High Resolution Package—The High Frame Rate/High Resolution (HFR/HR) Diagnostics Package provides programmable frame rates and high optical resolution performance. It consists of a telecentric optical system, a trombone prism assembly, a pointing mirror assembly, digital camera and associated control electronics. The HFR/HR Package is capable of automatically tracking an object within the total field of view, while maintaining a sharp focus over a full object distance displacement range of 30 mm.

COLOR CAMERA | HFR/HR CAMERA | HiBMS CAMERA | ILLUMINATION PACKAGE | LOW LIGHT LEVEL CAMERA

Figure 6. CIR science diagnostics

Features:
- Automated Tracking—Capable of steering a 9x9 mm Instantaneous FOV (IFOV) over a total 46 mm dia. total FOV truncated to 37 mm horizontally and vertically
- 10mm/s maximum tracking speed
- Automated focus over 30 mm object depth; 5mm/s focus speed; telecentric
- Package may be programmed to sequentially operate in the 2 alternate modes
  - High Resolution Mode: 1024x1024 pixels at frame rates of 7.5, 15, or 30 fps
  - High Frame Rate Mode: 512x512 pixels at programmable frame rates of 60 or 110 fps
- Resolution is 20 lp/mm at 50% contrast in HR mode (0.009 mm at Nyquist limit)
- Event trigger capability

Color Camera Package—The Color Camera Package provides color imaging of combustion experiments. Color images are used by the crew and ground personnel for checkout and verification during pre- and post-combustion events.

Features:
- Field of view: 90 to 350 mm square
- Resolution: 2.8 to 0.7 lp/mm at Nyquist limit (0.18 mm maximum resolution)
- Frame Rate: 30 fps
- Spectral range: 400 to 700 nm

Low Light Level Packages (UV and IR)—The Low Light Level (LLL) packages provide images of events or objects at low radiance levels. A LLL package consists of a digital monochrome camera coupled to an intensifier with fast numerical aperture optics and provision for spectral filtering of the transmitted illumination.

LLL-UV Features:
- Optical System
  - FOV: 42 and 100 mm square
  - Resolution: wide field: 2.8 lp/mm (0.18 mm); narrow field: 6.7 lp/mm (0.075 mm)
  - Provision for manually inserted filters. Providing 310 nm filter with a 10 nm FWHM bandwidth.
  - Manual iris and focus
- Camera
  - Spectral range: 220 to 850 nm
  - Sensitivity: 5x10E-8 ft. candles binned
  - Intensifier: Gen II
  - Frame rate 60 fps

LLL-IR Features:
- Optical System Parameters
  - FOV: 45 to 180 mm square
  - 2X motorized zoom capability, and two objective lenses.
  - Resolution: wide field 3.4 lp/mm (0.15 mm); narrow field: 6.8 lp/mm (0.07 mm)
  - Motorized focus and iris
  - Accepts standard bandpass filters. Filters are removable for broadband imaging capability
- Camera
  - 400 to 900 nm (IR shifted)
  - Sensitivity: 5x10E-8 ft-candles binned
  - Intensifier: Gen III Ultra

Mid-IR Camera Package—A Mid-Infrared Camera Package produces images of events or objects emitting in the range of 3600 to 5000 nm. The package may contain a mechanism for inserting filters into the optical path. The wavelength of interest can be manually selected prior to Package attachment to the Optics Bench. A standard lens interface is used so that alternative lenses can be installed.

Illumination Package—The Illumination Package provides an illumination source to the chamber and is used in conjunction with diagnostics packages that require backlight illumination. It consists of a collimated optical system with a software controlled selector mirror and three illumination sources. One illumination source is a current stabilized Tungsten Halogen lamp which can be used for radiometric calibration. The other two sources are laser diodes. One laser diode includes a holographic diffuser and apodizer for uniform, coherence interference free illumination.

Features:
- 80 mm diameter collimated beam
- Tungsten Halogen Source
  - 0.6 lumens/ mm2; 50% illumination field uniformity
  - 7.6 milliradians divergence
  - 3000 K color temperature; 2% stability
- Diffuse Laser Diode Source
  - 10 mW coupled power minimum; programmable level
  - 60% illumination field uniformity
  - Peak Wavelength: between 660 and 690 nm points
  - Can be synchronized with the imaging packages
- Spectral Bandwidth: 7 nm maximum at 50%

SCIENCE UTILIZATION

It is expected that the CIR will provide most of the required capability with a small amount of unique hardware developed for each investigation. When possible, similar investigations will be flown at the same time to increase the use of common hardware and diagnostics. As a way to further reduce the amount of new hardware that needs to be supplied for each investigation, a set of three multi-user chamber inserts is being designed to support classes of experiments.[7] Other inserts for singular investigations having requirements not able to be met by the multi-user inserts will be developed as resources permit. Commercial and international investigations will provide their own chamber insert or other resources in exchange for use of a multi-user insert. A total of fifteen flight and flight-definition investigations supported by the microgravity science program and one or more commercial and international investigations are currently foreseen to use the CIR over the first few years of operation. Table 1 shows the expected utilization of the CIR from launch through mid-2007. The columns list the launch dates for the three FCF racks and the expected order for the multi-user inserts and the combustion science investigations.

Droplet Combustion

Four investigations are currently planning to study the combustion of small, spherical droplets of pure and bicomponent alcohol and hydrocarbon fuels. Liquid fuels are a primary source for energy production in the world and the study of their combustion has been ongoing for decades. Nearly all practical uses of combustion involve non-premixed conditions; these are more easily studied using a well defined system such as an isolated droplet. The study of droplet combustion has been and remains a classic combustion problem. One of the investigations, Droplet Combustion Experiment-2 (DCE-2), is a reflight investigation. The Bi-Component Droplet Combustion Experiment (BCDCE) has passed its two science reviews, the Sooting Effects in Droplet Combustion (SEDC) has passed its first review, and the Dynamics of Droplet Combustion and Extinction (DDCE), is in the early phase of development. The hardware insert will be based upon the internal apparatus developed for the Droplet Combustion Experiment.[8,9] This structure contains the droplet deployment mechanisms, hot wire ignitors, fuel supply system, and gas mixing fan. The droplet is generated by issuing fuel from a pair of needles brought together in the center of the test region. The needles are stretched apart slightly after the droplet reaches the proper size (1 to 6 mm dia.) and then are withdrawn simultaneously at a high acceleration to deploy the droplet. At the moment of droplet deployment, the hot-wire ignitors are activated to ignite the droplet and then they are withdrawn. The droplet may be deployed into free space or onto small ceramic fibers. The structure is mostly open to permit viewing of the droplet and flame.

The DCE-2 reflight will further explore droplet combustion behaviors, especially those related to extinction phenomena, observed during its first flights on the MSL-1 flights in April and July 1997.[10] The droplet and flame size will be imaged throughout the burn. The experiment will provide benchmark experimental data sets that can be used for comparison to theoretical predictions of liquid-phase and gas-phase steady and unsteady phenomena, and extinction phenomena. Earlier experiments revealed or verified several phenomena unique to low-gravity, including radiative quenching of the flame and burning at lower oxygen concentrations than in normal gravity.

TABLE 1. Utilization traffic model for the Fluids and Combustion Facility as of October 2000 (Rev. F Assembly).

Date	9/04	2/05	10/05	6/05	4/06	7/06	10/06	2/07	5/07
Flight	UF-3	UF-5	17A	UF-6	UF-7	LF-1	LF-2	LF-4	LF-5
Launch: Facility, Insert, or Exp.	CIR, FIR MDCA DCE-2 BCDCE	D-3 D-4 COMM-A	FEANICS-A SIBAL FIST COMM-B	SAR	MGFA-A GF-1 GF-2		FEANICS-B TIGER-3D SF-4 SF-5	MGFA-B INT (SF6)	GF-3 GF-4
Landing: Facility, Insert, or Exp.		DCE-2 BCDCE	MDCA D-3 D-4 COMM-A		FEANICS-A SIBAL FIST	COMM-B		MGFA-A GF-1 GF-2	FEANICS-B TIGER-3D

CIR is the Combustion Integrated Rack; FIR is the Fluids Integrated Rack; SAR is the Shared Accommodations Rack; MDCA is the multi-user droplet combustion apparatus; D is a droplet combustion investigation; FEANICS is the multi-user solid fuel apparatus; SF is a solid fuel combustion investigation; MGFA is the multi-user gaseous fuel apparatus; GF is a gaseous fuel combustion investigation; COMM is a commercial investigation; and INT is an international investigation

Another isolated, quiescent droplet experiment, BCDCE, has as its focus the internal liquid fluid dynamics and combustion of bicomponent droplets.[11] These tests use droplets composed of a mixture of low volatility and high volatility fuels. As the droplet burns, the high volatility component burns off preferentially and the low volatility component is enriched at the droplet surface. At a certain time near when the low volatility fraction near unity, the droplet surface heats rapidly and a contraction in flame size is observed. This experiment will be the first to study how the internal flow dynamics and combustion of a burning droplet are driven by liquid species transport and capillary forces.

Sooting behaviors of droplets are the focus of the SEDC investigation.[12] The goal of this experiment is to perform detailed quantitative measurements of the soot concentration and temperature distributions and soot morphology in single, isolated burning droplets. Based on observations in the ground-based reduced-gravity facilities, the formation and presence of soot can modify the burning droplet behavior. An understanding of the formation, transport, and oxidization of soot is important for control of desired or undesirable sooting.

In contrast to the first three droplet investigations in a quiescent environment, the fourth investigation, DDCE, plans to study droplet combustion in the presence of low-speed convective flows such as may be found in the ventilation systems of space vehicles.[13] This investigation will focus on understanding the influences of convection on the radiative extinction that occurs when excessive radiative heat loss from the flame zone leads to flame extinction. The investigation will improved the understanding of enhanced fire safety margins in spaceflight as well as help to interpret the measurements made of freely deployed droplets having a small, residual velocity.

Solid Fuel Combustion

Seven investigations are currently planning to the study of the combustion of solid fuels. The study of solid fuel combustion is important for the development of better material flammability tests and predictions, and models of flame ignition, spread, and extinction in solid materials. Improved fire prevention and extinguishment on the earth and in spacecraft are potential benefits of this research. Unwanted fires result in a significant number of deaths and lost property each year on the earth, and the possibility of an accidental fire in a spacecraft remains a concern. The first three investigations discussed below passed their first science reviews and are in the requirement definition and engineering concept formulation phase. The remaining are in the science concept formulation phase. Preliminary requirements from these investigations are guiding the development of a chamber insert capable of being used by as many investigations as possible within the resources available for its development.[14] Most of the investigations require a sample holder, a flow duct to provide a low speed flow environment, an ignition system, and a clear volume for imaging of the flame and solid fuel surface.

One investigation, Solid Inflammability Boundary at Low Speed (SIBAL) studies the effect of low-speed, concurrent flow on the spreading and extinction processes of flames over a thin, solid fuel.[15] The investigation seeks to verify the theoretically predicted extinction boundary. In particular, the low-speed quenching limits and the existence of the critical oxygen flammability limit are sought. Theoretical models and previous microgravity experiments show that flame spread and extinction phenomena in low-speed flows are fundamentally different from that found in higher-speed flows, such as are encountered on earth. The investigation will validate a model of flame spread and extinction that predicts the existence of a critical low oxygen limit in concurrent flow. The existence of this fundamental limit is of scientific interest and has implications for spacecraft fire safety.

Another investigation studying solid fuels in low-speed flows is the Transition from Ignition to Flame Growth under External Radiation in 3-D (TIGER-3D) investigation.[16] The objective of this investigation is to study the processes that control the ignition and subsequent transition to flame spread for solid fuels. The effects of external radiant flux distribution and flow velocity, sample configuration, and oxygen concentration will be studied. Samples of paper and polymethylmethacrylate (PMMA) will be placed into a flow duct. Once the gas flow is established, the sample will be radiantly ignited. The results will be used to validate an extensive computer model that predicts initiation of fire and its growth in microgravity with material characteristics as inputs to the model. The model could be further developed to apply to the normal gravity selection of materials for terrestrial applications.

The Forced Ignition and Spread Test (FIST) investigation seeks to develop a standard testing method to assess the flammability of solid materials for spacecraft applications.[17] A new flammability apparatus will be tested in anticipation that it will better reflect the potential ambient conditions of space-based environments. The goal is to use the apparatus to obtain more appropriate flammability diagrams for common materials used in space facilities. The sample fuels are PMMA and composites such as those used on aircraft. The apparatus under test uses a radiant panel to provide an incident flux to a large portion of the fuel surface. A low speed flow is passed over the fuel to simulate the flow environment aboard spacecraft.

Ignition is provided by a hot wire located in the region where vapors from the fuel pass. The time to ignition, flame-spread rate, and surface temperature are measured as the amounts of radiant flux and exposure time are varied. Theoretical modeling and normal gravity experiments will support the tests. The improved testing method could lead to a better determination of the fire hazard characteristics of materials for spacecraft. The goal is to develop and validate a simple model based on the material properties and the critical heat flux that will allow materials to be ranked in terms of their propensity to ignite and spread rapidly.

An investigation using both low speed flow or no flow is Radiative Enhancement Effects on Flame Spread (REEFS).[18] The effects of inert components such as carbon dioxide in the atmosphere and low speed flows on flame spread rates across solid fuels will be studied. Since fires in enclosures with insufficient oxygen for complete combustion often produce carbon monoxide and unburned gaseous fuel molecules, some tests will be done in the presence of small amounts of fuel to see if the flame will burn stronger or faster. The study of fires with carbon dioxide as a diluent is particularly relevant to fire safety on the International Space Station, as its fire extinguishers will use carbon dioxide, or in a Martian environment.

An investigation named Analysis of Thermodiffusive and Hydrodynamic Instabilities in Near-extinction Atmospheres (ATHINA) will study the details of the breakup of a steadily propagating, uniform flame front into a corrugated flame or small, individual flamelets.[19] In normal gravity, buoyancy overwhelms these instabilities and produces planar flames. Unstable flame fronts have been observed in microgravity for diffusion flames of candles and thin solid fuels, often in cases where there is significant heat loss to a nearby cold, solid surface. The spaceflight investigation will use wide samples in a low-speed flow of air. Measurements of the flame shape and structure as it forms the flamelets will be made for comparison to a theoretical model.

Finally, an investigation characterizing smolder and its transition to flaming has just begun.[20] Smoldering is characterized by a heterogeneous surface reaction that propagates through the surface and interior of porous combustible materials. This is of interest as a serious fire risk in spacecraft is from overheated electrical components. There is currently only limited information on the behavior of smoldering in a space facility environment. This study seeks to understand the controlling mechanisms of smoldering combustion and when smolder transitions into open flaming.

Gaseous Fuel Combustion

Six investigations are currently planned for the study of various types of gaseous fuel combustion. Both premixed and nonpremixed gaseous combustion using nozzles of various sizes, flame vessels and tubes, and porous spherical burners will be studied. Gaseous combustion occurs in many practical systems as well as in unwanted fires. The use of gaseous fuels simplifies the study of the main processes in combustion, chemical reaction, and heat and mass transfer. The Cool Flames investigation passed its first science review; the remainding are in the science concept formulation phase of their development and will undergo several science reviews. For as many experiments as possible, the hardware insert will be based upon the chamber insert developed for the Laminar Soot Processes experiment flown in the Combustion Module.[21,22] This structure contains a small fuel nozzle and hot wire ignitor, and a far-field thermocouple rake, flame radiometer, and thermophoretic soot samplers. During the experiment, fuel issues from the nozzle into a quiescent chamber filled with oxidizer. A hot wire ignitor positioned near the nozzle tip ignites the flame. When the data collection is complete, the fuel flow is ended and the flame extinguishes. The reflight of a commercial investigation studying the efficacy of water mist as a fire suppressant is also planned.

One of the premixed flame investigations, Cool Flames, will study diffusively controlled, low-temperature oxidation reactions and cool flames under static conditions.[23] The experiment will be conducted in a small, heated, quartz flask filled with a mixture of fuel and oxygen. The gases will auto-ignite and react at low temperatures over the course of seconds to days, depending on the initial conditions. An improved understanding of low temperature oxidation reactions and cool flames will improve the design and selection of operational parameters for internal combustion engines, and could improve the understanding of engine knock, engine run-on, and autoignition.

Another premixed flame investigation, Water Mist, uses a premixed flame to test the efficacy of fine water mists for fire suppression.[24] The objective is to study the fundamental interaction of a flame with a water mist in a simple, well-defined experimental setup such as can be produced in microgravity. The use of water mist technology is being considered as a replacement for halogen-based chemical agents. The first flight of this investigation is scheduled for 2002 in the Combustion Module-2 facility aboard the Space Shuttle. This investigation is sponsored by the NASA Center for Commercial Applications of Combustion in Space.

A third premixed flame investigation is Lean Premixed Turbulent Flames.[25] The objective of this experiment is to characterize flame structures and flowfields of lean premixed laminar and turbulent flames. Turbulent combustion, which involves a complex coupling of chemical and fluid mechanics, is a crucial issue for combustion. The microgravity environment will provide data needed by the experiment to understand the coupling between local effects and field effects on flame structures. The practical applications from this investigation will be to guide the development of turbulent combustion models to include the effects of gravity. This would allow enhancement of the burning rates and volumetric power density in many heating and power generating systems.

Another investigation studying turbulence, the Pulsed-Fully Flames (PUFF) experiment, uses nonpremixed combustion to increase the fundamental understanding of the fuel/air mixing and combustion behavior of fully modulated (pulsed), turbulent diffusion flames.[26] Specifically, this investigation will determine the mechanisms responsible for flame length decrease of these flames as compared to unmodulated flames, how the mixing and combustion characteristics are impacted by buoyancy, the nature of turbulent fuel puffs at high Reynolds number in the fully momentum-dominated regime, and the conditions under which these flames behave like steady diffusion flames. Microgravity allows the flame flickering to be produced in a controlled manner. This investigation has applications to pulsed combustion devices such as those used in furnaces, heaters, dryers, and incinerators. Pulsing accelerates the fuel/air mixing and combustion rate, thereby increasing the thermal efficiency and heat transfer, while reducing the formation of pollutants such as soot, carbon monoxide, and NOx.

Two investigations using a porous sphere burner will study various aspects of nonpremixed diffusion flames. One is the Structure and Response of Spherical Diffusion Flames (s-Flame) investigation.[27] The investigation will study the structure and dynamics of diffusion flames in simple, well-defined flow fields. The emphasis is on various issues related to unsteadiness, kinetics and extinction, flame front instabilities, vortical flow motion, and partial premixing. Discharging fuel from a porous spherical burner into a quiescent, oxidizing ambient atmosphere generates a spherically symmetric diffusion flame. The practical application of this investigation will lead to approaches for achieving energy conversion efficiencies and reduction of pollution in such flames.

The other investigation using the porous sphere burner is Flame Design.[28] The investigation will study the relative importance of structure and flow inversion on soot inception and flame extinction and determine which is the dominant mechanism for soot suppression at high stoichiometric mixture fraction. The microgravity flames are uniquely capable of allowing independent variation of the convective direction and flame structure while maintaining constant flame temperature. The investigation studies the effects of fuel flowing into quiescent oxidizer or the reverse, oxidizer flowing into quiescent fuel (flow inversion). It will also study the effects of removing nitrogen from air, leaving behind the oxygen, and adding the nitrogen to the fuel (structure inversion). Four flames will be studied: i) fuel issuing into air, ii) diluted fuel issuing into oxygen, iii) air issuing into ethylene, and iv) oxygen issuing into diluted fuel. Preliminary work in the reduced-gravity drop tower shows dramatic reduction in soot for cases ii and iv. The study of these flames will lead to designs that best optimize efficiency and minimize pollutants, specifically soot and NOx.

CIR STATUS

In April 1999, a Preliminary Design Review of the CIR was held and the CIR proceeded to Phase C/D design and development. At the FCF PDR in February 2001 the CIR Delta-PDR was held. Engineering model hardware for the CIR is currently being assembled and tested. Rack-level engineering model testing is expected to begin in the fall of 2001, and a Critical Design Review (CDR) of the CIR is planned in early 2002.

ACKNOWLEDGEMENTS

The NASA Office of Space Flight and the NASA Office of Biological and Physical Research provide funding for the microgravity combustion program and spaceflight hardware. The contributions to this work of the Project Scientists from the NASA Glenn Research Center and the National Center for Microgravity Research on Fluids and Combustion are gratefully acknowledged. The authors also gratefully acknowledge the FCF project team at the NASA Glenn Research Center and the FCF/CIR team at the Logicon and Analex Corporations for their excellent work and contributions to develop the FCF Combustion Integrated Rack.

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